Radioactive Isotopes

Absolute dating and melt origin constraints

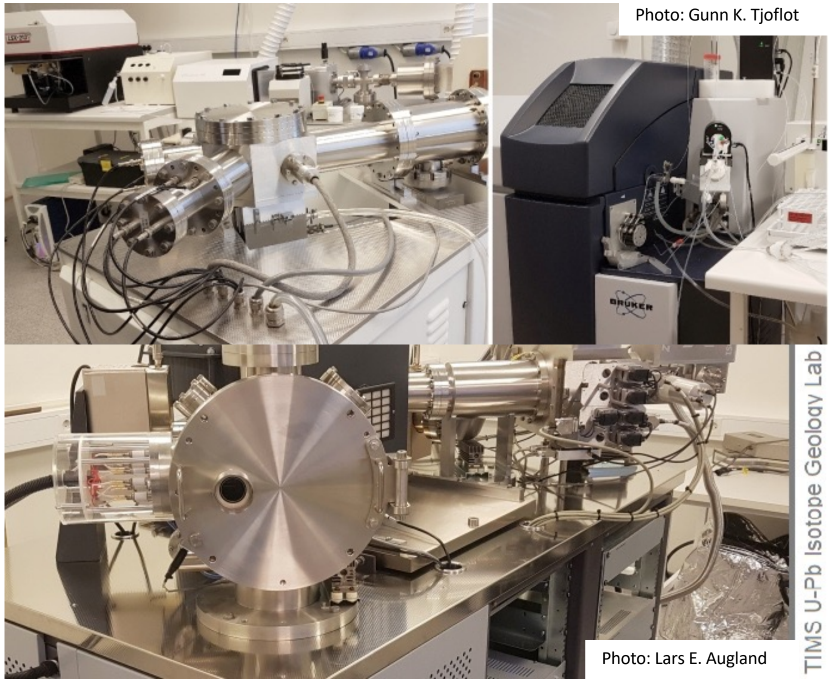


Photo: Gunn K. Tjoflot

Photo: Lars E. Augland

TIMS U-Pb Isotope Geology Lab

Radioactive isotopes

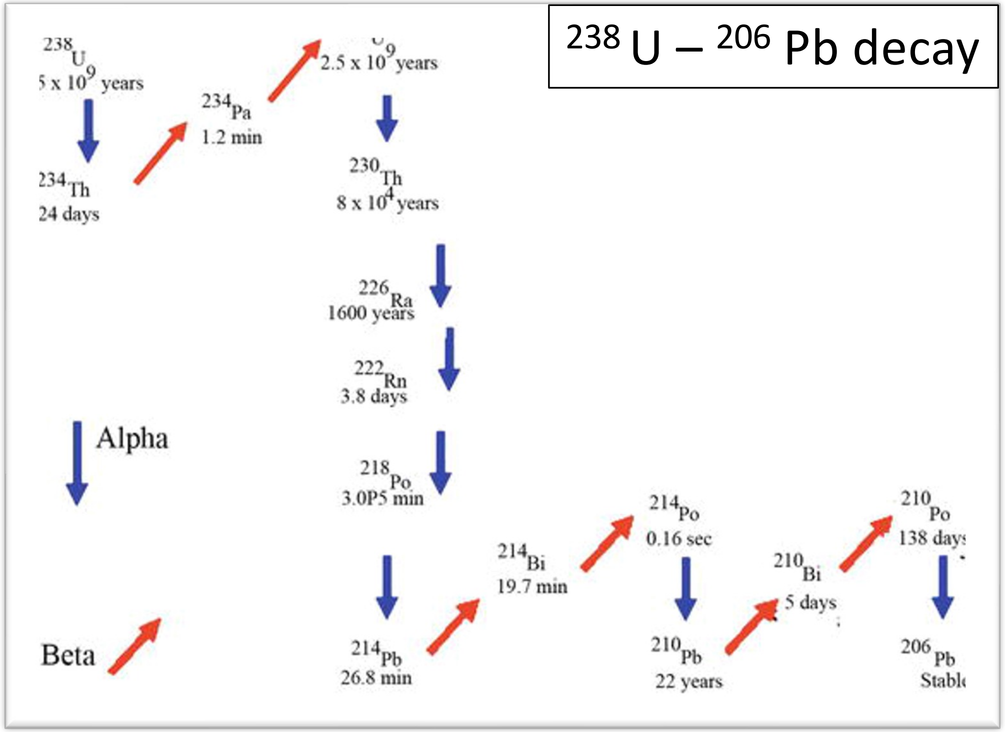
There are many naturally occurring isotopes that are radioactive – They decay to a stable or observationally stable isotope over time.

Some of these isotopes decay so slowly that they are useful as geochronometers – their half-lifes are long enough to calculate geological timespans (e.g. ^{238}U decays to ^{206}Pb in 4.47 x 10^9 years).

This also means that some radioactive isotopes are inherited from the original composition of the Earth.

The relationships of certain isotopes can be used as tracers – Telling us something about the origin of e.g. a volcanic rock

(Ellam, 2021)


^{238}U – ^{206}Pb decay

(Salih Muhammad, 2020)

The most common radioactive isotopes used in geology

Others are also used to evaluate sources of melting and mantle influence in volcanics

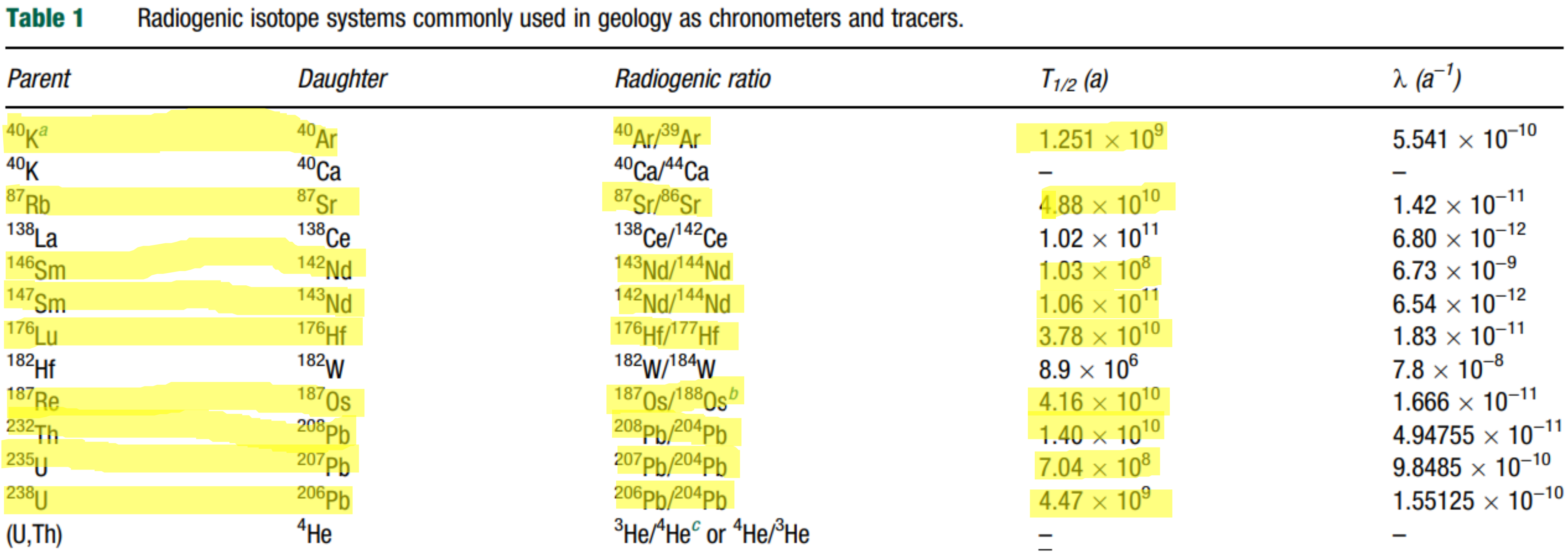


Table 1 Radiogenic isotope systems commonly used in geology as chronometers and tracers.

Parent	*Daughter*	*Radiogenic ratio*	$T_{1/2}$ (a)	λ (a^{-1})
$^{40}K^{a}$	^{40}Ar	$^{40}Ar/^{39}Ar$	1.251×10^{9}	5.541×10^{-10}
^{40}K	^{40}Ca	$^{40}Ca/^{44}Ca$	–	–
^{87}Rb	^{87}Sr	$^{87}Sr/^{86}Sr$	4.88×10^{10}	1.42×10^{-11}
^{138}La	^{138}Ce	$^{138}Ce/^{142}Ce$	1.02×10^{11}	6.80×10^{-12}
^{146}Sm	^{142}Nd	$^{143}Nd/^{144}Nd$	1.03×10^{8}	6.73×10^{-9}
^{147}Sm	^{143}Nd	$^{142}Nd/^{144}Nd$	1.06×10^{11}	6.54×10^{-12}
^{176}Lu	^{176}Hf	$^{176}Hf/^{177}Hf$	3.78×10^{10}	1.83×10^{-11}
^{182}Hf	^{182}W	$^{182}W/^{184}W$	8.9×10^{6}	7.8×10^{-8}
^{187}Re	^{187}Os	$^{187}Os/^{188}Os^{b}$	4.16×10^{10}	1.666×10^{-11}
^{232}Th	^{208}Pb	$^{208}Pb/^{204}Pb$	1.40×10^{10}	4.94755×10^{-11}
^{235}U	^{207}Pb	$^{207}Pb/^{204}Pb$	7.04×10^{8}	9.8485×10^{-10}
^{238}U	^{206}Pb	$^{206}Pb/^{204}Pb$	4.47×10^{9}	1.55125×10^{-10}
(U,Th)	^{4}He	$^{3}He/^{4}He^{c}$ or $^{4}He/^{3}He$	–	–

(Ellam, 2021)

Radiometric dating

Uranium – Lead dating

As mass spectrometers were developed mainly during the Manhattan Project (1942-1946), geologists saw the potential to use the decay of uranium isotopes to stable lead isotopes as a geological chronometer (Ellam, 2021). Patterson (1956) determined the age of the Earth by U-Pb dating of a meteorite troilite to 4.55 ± 0.07 x 10^9 Years. The methods evolved during the latter half of the 1900s (Ellam, 2021), and several methods for both in situ anaylsis and laboratory analysis were developed (Schaltegger et al., 2015).

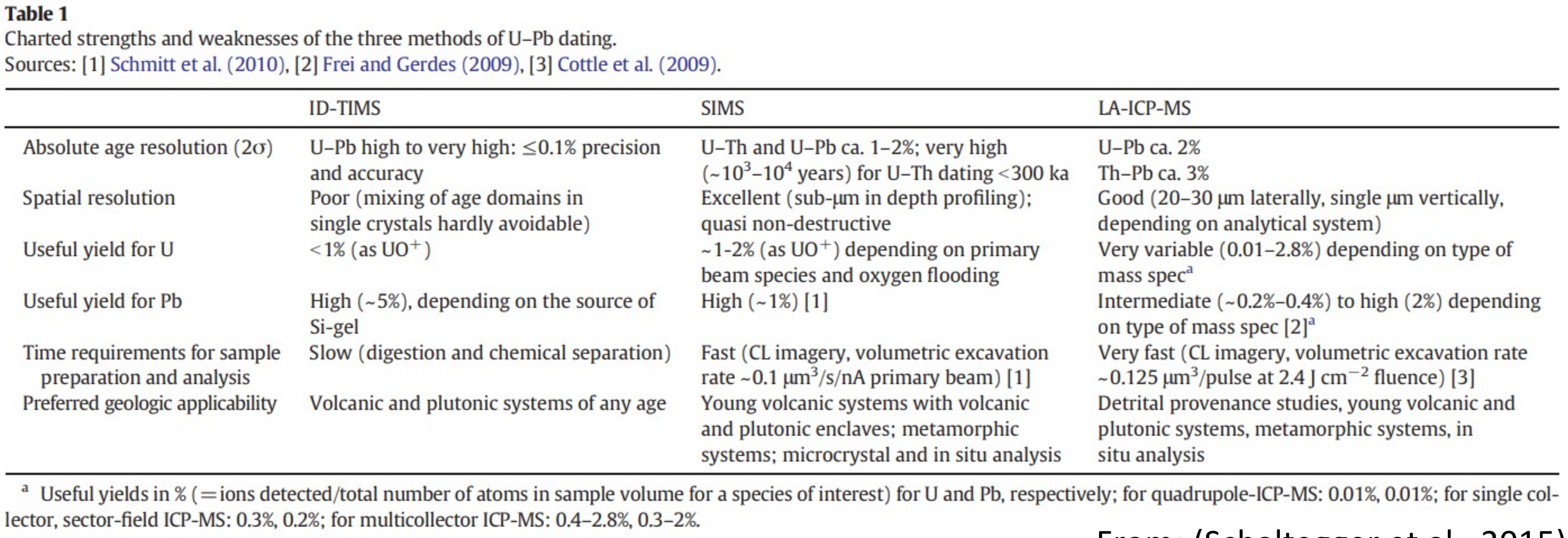


Table 1
Charted strengths and weaknesses of the three methods of U–Pb dating.
Sources: [1] Schmitt et al. (2010), [2] Frei and Gerdes (2009), [3] Cottle et al. (2009).

	ID-TIMS	SIMS	LA-ICP-MS
Absolute age resolution (2σ)	U–Pb high to very high: ≤0.1% precision and accuracy	U–Th and U–Pb ca. 1–2%; very high (~10^3–10^4 years) for U–Th dating <300 ka	U–Pb ca. 2% Th–Pb ca. 3%
Spatial resolution	Poor (mixing of age domains in single crystals hardly avoidable)	Excellent (sub-μm in depth profiling); quasi non-destructive	Good (20–30 μm laterally, single μm vertically, depending on analytical system)
Useful yield for U	<1% (as UO^+)	~1-2% (as UO^+) depending on primary beam species and oxygen flooding	Very variable (0.01–2.8%) depending on type of mass spec[a]
Useful yield for Pb	High (~5%), depending on the source of Si-gel	High (~1%) [1]	Intermediate (~0.2%–0.4%) to high (2%) depending on type of mass spec [2][a]
Time requirements for sample preparation and analysis	Slow (digestion and chemical separation)	Fast (CL imagery, volumetric excavation rate ~0.1 μm^3/s/nA primary beam) [1]	Very fast (CL imagery, volumetric excavation rate ~0.125 μm^3/pulse at 2.4 J cm^{-2} fluence) [3]
Preferred geologic applicability	Volcanic and plutonic systems of any age	Young volcanic systems with volcanic and plutonic enclaves; metamorphic systems; microcrystal and in situ analysis	Detrital provenance studies, young volcanic and plutonic systems, metamorphic systems, in situ analysis

[a] Useful yields in % (=ions detected/total number of atoms in sample volume for a species of interest) for U and Pb, respectively; for quadrupole-ICP-MS: 0.01%, 0.01%; for single collector, sector-field ICP-MS: 0.3%, 0.2%; for multicollector ICP-MS: 0.4–2.8%, 0.3–2%.

From: (Schaltegger et al., 2015)

Radiometric dating

Uranium – Lead dating

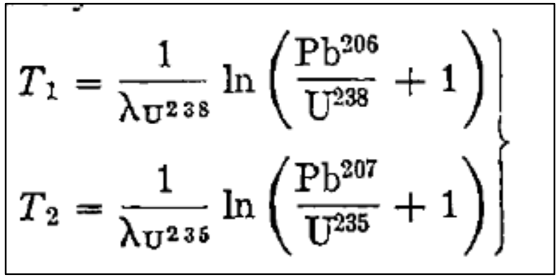
U-Pb age is calculated by the equation to the right →
λ is the decay constant for each system.

The ages calculated for each system (T_1, T_2) should be equal as long as:

1. No loss of Uranium or Lead (closed system)
2. No gain or loss of intermediate phases (e.g. radon)
3. Proper corrections for initial lead
4. Proper chemical analysis and decay constants

(Wetherill, 1956)

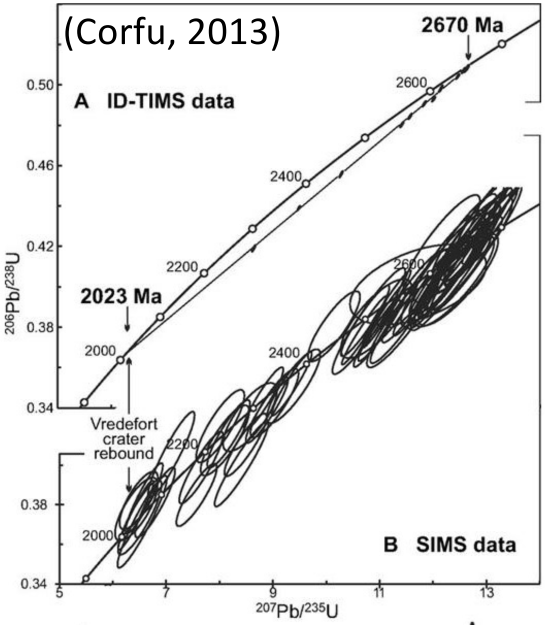
Ages are then plotted in a concordia diagram. Points that fall off the concordia curve but still adhere to a straight line can be used to infer an event that has led to loss of lead (e.g. metamorphic event). These points form a discordant line and intercept the concordia curve at true age (upper intercept) and age of alteration (lower intercept)(Corfu, 2013).



$$T_1 = \frac{1}{\lambda_{U^{238}}} \ln\left(\frac{Pb^{206}}{U^{238}} + 1\right)$$

$$T_2 = \frac{1}{\lambda_{U^{235}}} \ln\left(\frac{Pb^{207}}{U^{235}} + 1\right)$$

(Wetherill, 1956)

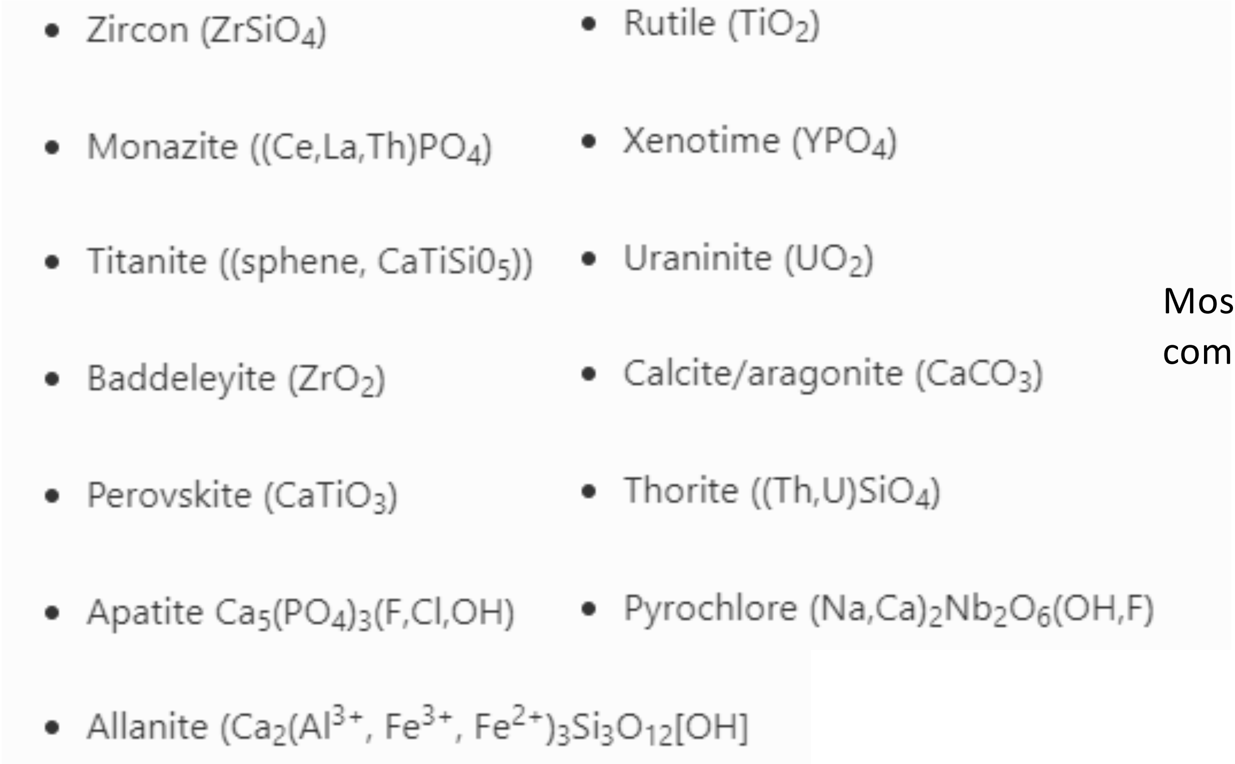


(Corfu, 2013)

Radiometric dating

Uranium – Lead dating

Minerals:



- Zircon ($ZrSiO_4$)
- Monazite ($(Ce,La,Th)PO_4$)
- Titanite ((sphene, $CaTiSi0_5$))
- Baddeleyite (ZrO_2)
- Perovskite ($CaTiO_3$)
- Apatite $Ca_5(PO_4)_3(F,Cl,OH)$
- Allanite ($Ca_2(Al^{3+}, Fe^{3+}, Fe^{2+})_3Si_3O_{12}[OH]$
- Rutile (TiO_2)
- Xenotime (YPO_4)
- Uraninite (UO_2)
- Calcite/aragonite ($CaCO_3$)
- Thorite ($(Th,U)SiO_4$)
- Pyrochlore $(Na,Ca)_2Nb_2O_6(OH,F)$

Most useful minerals have little to none common Pb, but care should be taken.

(Parrish, 2013)

Radiometric dating

Rubidium-Strontium dating

- A widely used and powerful dating tool for igneous rocks, metamorphic events and in special circumstances fluid events, volcanic eruptions and sedimentary sequences.
- Rb-87 decays to Sr-87, with a half-life of approx. 49 billion years.
- Different mineral phases/mineral phase compared to whole-rock, needed for calculating isochron.
- ID-TIMS gives the best result, but in-situ techniques are being utilized (CC-MC-ICPMS/MS)(Bevan et al., 2021)
- Low closing temperature makes the Rb-Sr system susceptible to resetting (but useful for e.g. metamorphic events, hydrothermal events).
- Uncertainties are generally higher than e.g. CA-ID-TIMS U-Pb dating, but decent results are possible with state of the art equipment and procedures (Nebel et al., 2011).

$$\boxed{\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}(t) = \frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}(t_0) + \frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}\left(e^{\lambda t} - 1\right)}$$

$$\Big\downarrow$$

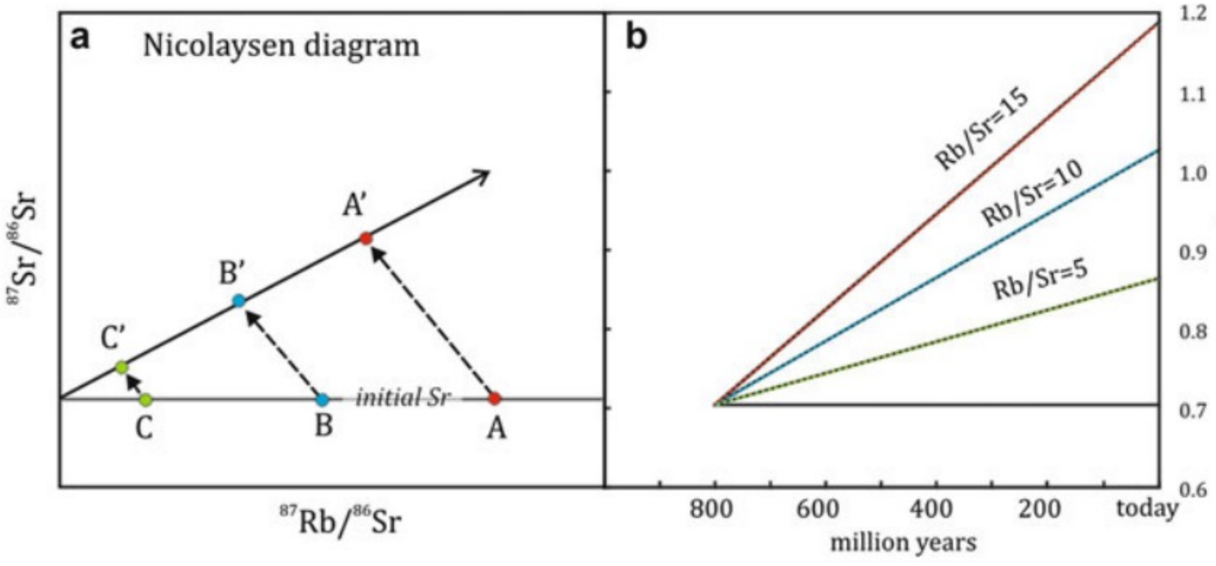
$$\boxed{t = 1/\lambda \cdot \ln\left\{1 + \left[\left(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}\right) - \left(^{87}\mathrm{Sr}/^{86}\mathrm{Sr}\right)_{\mathrm{initial}}\right] / \left(^{87}\mathrm{Rb}/^{86}\mathrm{Sr}\right)\right\}}$$

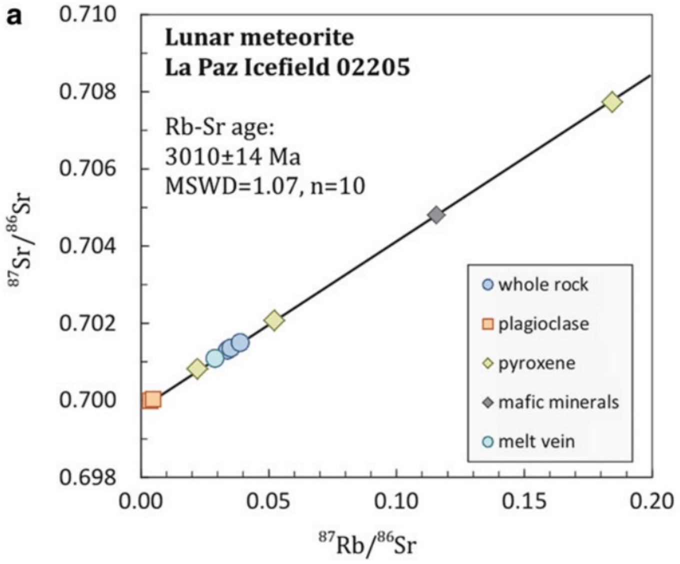
Radiometric dating

Rubidium-Strontium dating

Isochron plotting:

The slope of the isochron line gives the age.





(Nebel et al., 2011)

Radiometric dating

K-Ar and Ar-Ar dating

- Suitable for dating materials from the age of the Solar system to the Paleocene.
- K-Ar especially suited for potassium-bearing fine grained rocks (clays, glauconites…).
- K-Ar disadvantages: Thermally sensitive (metamorphism, slow cooling, reheating…), needs samples from two areas of a mineral – heterogeneties can be detrimental.
- Ar-Ar can date single grains – needs only one sample.
- Ar-Ar is less uncertain (typically less than 0.5%)
- Ar-Ar needs expensive equipment.
- Ar-Ar more calculation needed for corrections (artificial Ar isotopes and neutron irradiation).

K-Ar equation:

$$t = \frac{1}{\lambda}\ln\left(\frac{\lambda}{\lambda_e}\cdot\frac{{}^{40}\mathrm{Ar}^*}{{}^{40}\mathrm{K}} + 1\right)$$

Ar-Ar equation:

$$t_u = \frac{1}{\lambda}\ln\left\{\frac{\left({}^{40}\mathrm{Ar}^*/{}^{39}\mathrm{Ar}_{\mathrm{K}}\right)_u}{\left({}^{40}\mathrm{Ar}^*/{}^{39}\mathrm{Ar}_{\mathrm{K}}\right)_s}\left(e^{\lambda t_s} - 1\right) + 1\right\}$$

(Lee, 2015)

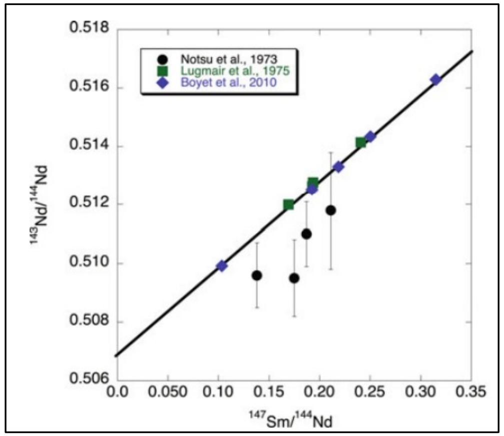
Radiometric dating
Sm-Nd and Lu-Hf dating

Sm-Nd:

- The most resillient to resetting – durable through high temperatures (can date rocks that have been through metamorphosis).
- Particularly useful for zircon-free rocks.
- Measures partial melting and crystal fractionation.
- Chondrite values are inferred to reflect the initial Earth values.

Lu-Hf:

- Like Sm-Nd – resillient to resetting.
- Needs different mineral phases to produce an isochron.
- Works for zircon-free rocks (e.g. ultramafic rocks)
- Subduction zone processes through lawsonite.
- Chondrite values are inferred to reflect initial Earth values.

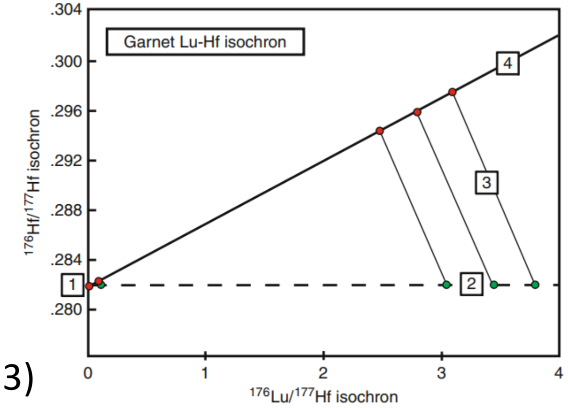


(Carlson, 2013)

Lu-Hf equation:

$$\text{Age} = \ln(\text{slope} + 1)/\lambda^{176}{}_{\text{Lu}}.$$

(Vervoort, 2013)

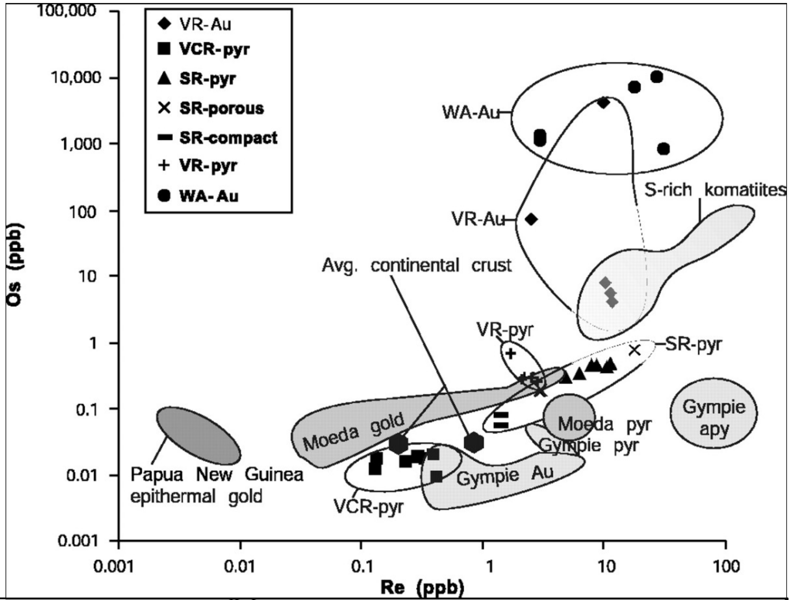


Radiometric dating

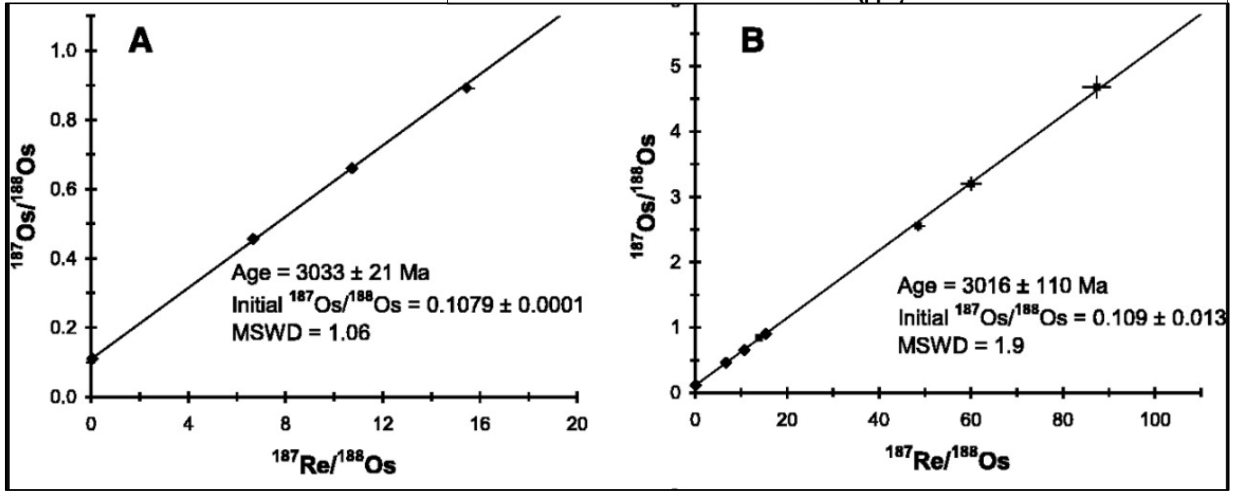
Re-Os dating

- Siderophile – concentrated in sulfides and metals.
- Can date sulfides and metals.
- Calculated by Isochron method.
- Re-Os isotopic ratios used to study the geochemical evolution of the mantle.
- Used to infer ancient crustal recycling into the mantle.
- Possibly a depth of melt indicator
- Dates metallic meteorites

(Morgan, 1998)



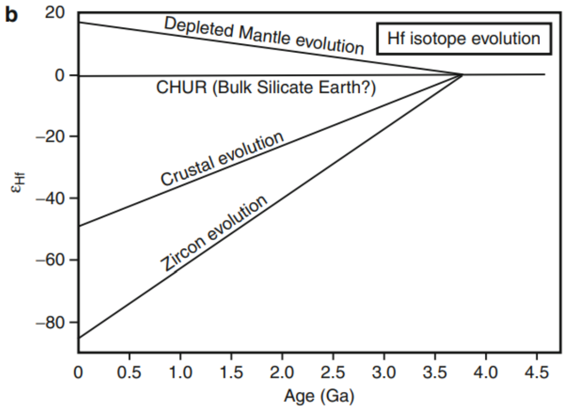
(Kirk et al., 2002)



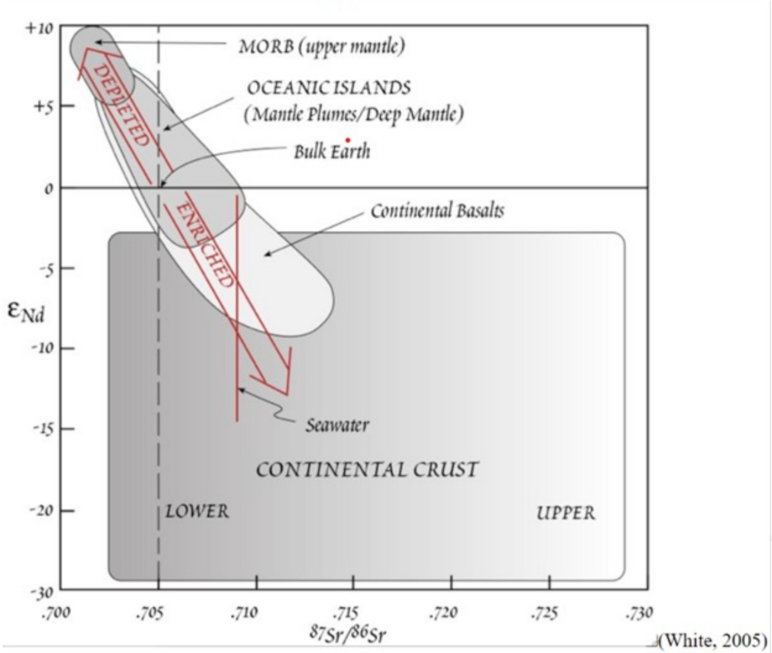
Tracer isotopes

Bulk Silicate Earth and CHUR

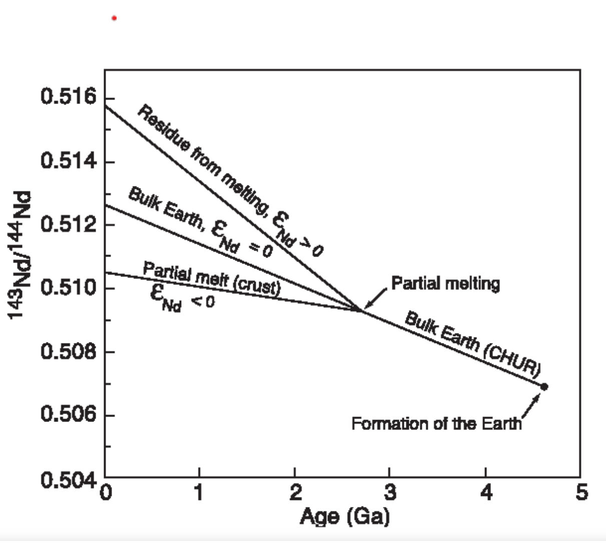
CHUR (the Chondritic Uniform Reservoir) is based on the assumption that the isotopic composition of refractory elements like Hf and Nd was homogenous in the solar nebula, and can be approximated by chondritic meteorites. Whether the Earth is strictly chondritic is debated, but CHUR still provides a valuable reference value for the initial Earth compostition. The lithophile and refractory charachter of both the Sm-Nd and the Lu-Hf systems makes them vital to understand the planetary evolution (Vervoort, 2013).



(Vervoort, 2013)



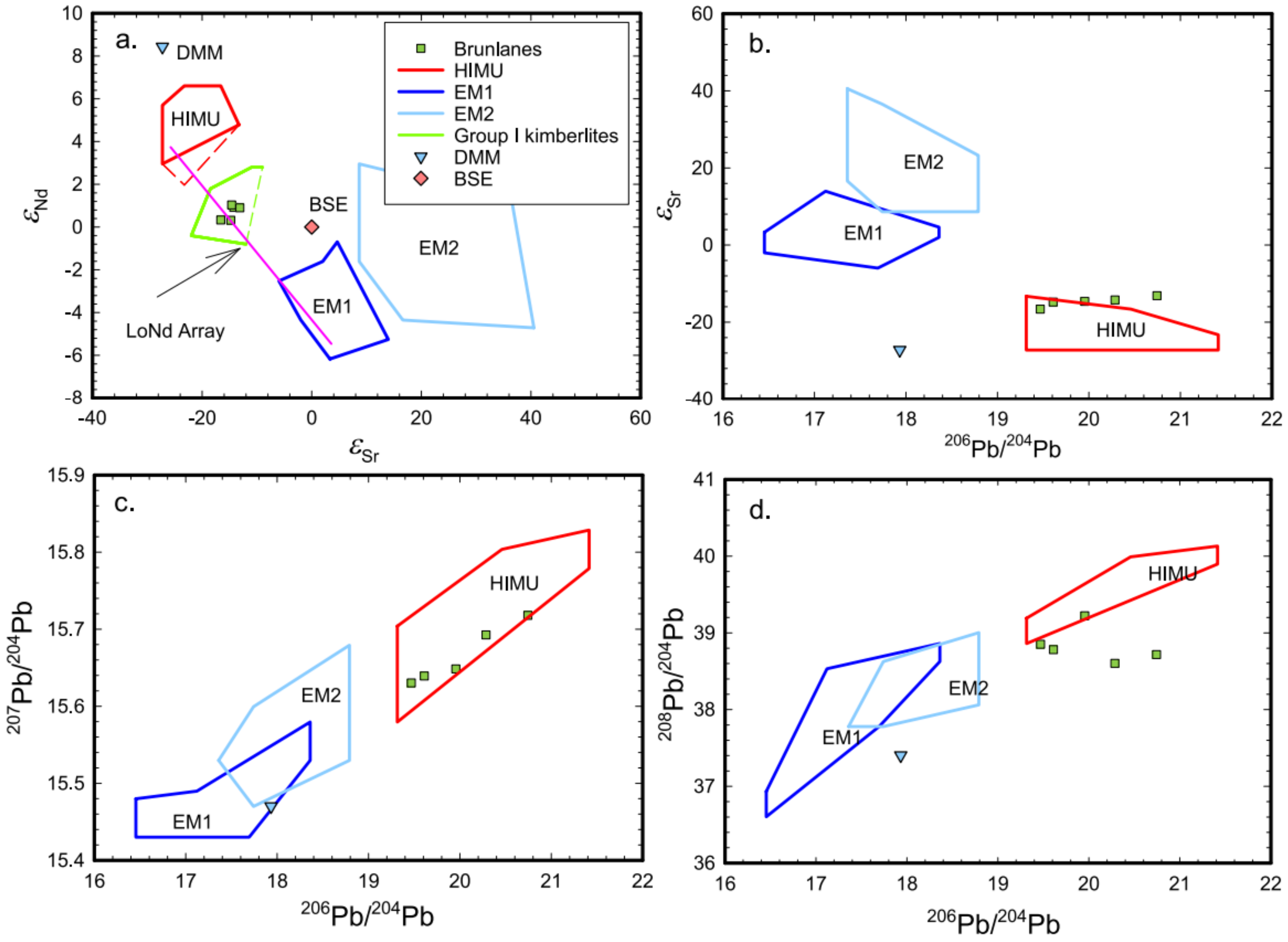
(White, 2005)



(Banner, 2004)

Tracer isotopes

Hyung et al. (2023) connected the alkalic ultramafic melilinite and nephelinite lavas from the Brunlanes area close to Skien (B1 in the Oslo Rift volcanic stratigraphy) to a mantle plume rising from the African LLSVP through comparisons of the geochemistry, trace elements, REE profile, major element composition, melt modelling and isotopic ratios. Data from the East African Rift System, Group 1 kimberlites and Siberian Flood Basalt Province was used to tie the Brunlanes rocks to its source.



(Hyung et al., 2023)

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